MEASUREMENT OF ϕ_3 IN $B^{\pm} \to D^{(*)}K^{\pm}$ DECAYS AT BELLE

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We present a measurement of the unitarity triangle angle ϕ_3 using a Dalitz plot analysis of the three-body decay of the D^0 meson from the $B^{\pm} \to D^{(*)}K^{\pm}$ process. The method employs the interference between D^0 and $\bar{D}^0$ to extract both the weak and strong phases. We apply this method to the 140 fb^{-1} of data collected by Belle experiment. The analysis uses $B^{\pm} \to DK^{\pm}$ and $B^{\pm} \to D^*K^{\pm}$ with $D^* \to D\pi^0$ modes, where the neutral D meson decays into $K_s\pi^+\pi^-$. From a combined maximum likelihood fit of $B^{\pm} \to DK^{\pm}$ and $B^{\pm} \to D^*K^{\pm}$ modes, we obtain $\phi_3 = 81^{\circ} \pm 19^{\circ} \pm 13^{\circ}(\text{syst}) \pm 11^{\circ}(\text{model})$. The 95% confidence interval is $35^{\circ} < \phi_3 < 127^{\circ}$.

1 Introduction

The determination of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements [1] is important to check the consistency of the Standard Model and search for new physics. Various methods using $B \to DK$ decays have been introduced [2] to measure the unitarity triangle angle ϕ_3 but the statistics accumulated by currently running experiments is not yet sufficient to constrain the value of ϕ_3 with a reasonable significance. A novel technique based on the analysis of the three-body decay of the D^0 meson [4] has a higher statistical precision compared to the methods based on branching fraction measurements.

This method is based on two key observations: neutral D^0 and $\bar{D}^0$ mesons can decay to a common final state such as $K_s\pi^+\pi^-$, and the decay $B^+ \to D^{(*)}K^+$ can produce neutral D mesons of both flavors via $\bar{b} \to \bar{c}u\bar{s}$ and $\bar{b} \to \bar{u}c\bar{s}$ transitions, where the relative phase θ_+ between the two interfering amplitudes is the sum, $\delta + \phi_3$, of strong and weak interaction phases. In the charge conjugate mode, the relative phase $\theta_- = \delta - \phi_3$, so both phases can be extracted from the measurements of such B decays and their charge conjugate modes. The phase measurement is based on the analysis of Dalitz distribution of the three body final state of the D^0 meson.

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In the Wolfenstein parameterization of the CKM matrix, the amplitudes of the diagrams contributing to the decay $B^+ \rightarrow \bar{D}^0(D^0)K^+$ are given by dominant $M_1 \sim V_{cb}^* V_{us} \sim A\lambda^3$ and color suppressed $M_2 \sim V_{ub}^* V_{cs} \sim A\lambda^3(\rho + i\eta)$ matrix elements. The two amplitudes interfere if the D^0 and $\bar{D}^0$ mesons decay into the same final state $K_s\pi^+\pi^-$; we denote the admixed state as $\tilde{D}$. Assuming no CP asymmetry in D decays, the amplitude of the B^+ decay is written as

$$M_+ = f(m_+^2, m_-^2) + re^{i\phi_3 + i\delta} f(m_-^2, m_+^2), \tag{1}$$

where m_+^2 and m_-^2 are the squared invariant masses of the $K_s\pi^+$ and $K_s\pi^-$ combinations, respectively, and $f(m_+, m_-)$ is the complex amplitude of the decay $\bar{D}^0 \rightarrow K_s\pi^+\pi^-$. The absolute value r of the ratio between the two interfering amplitudes is given by the product of the ratio $|V_{ub}^* V_{cs}|/|V_{cb}^* V_{us}| \sim 0.38$ and the color suppression factor.

Similarly, the amplitude of the charge conjugate B^- decay is

$$M_- = f(m_-^2, m_+^2) + re^{-i\phi_3 + i\delta} f(m_+^2, m_-^2). \tag{2}$$

Once the functional form of f is fixed by choosing a model for $\bar{D}^0 \rightarrow K_s\pi^+\pi^-$ decays, the $\tilde{D}$ Dalitz distributions for B^+ and B^- decays can be fitted simultaneously by the above expressions for M_+ and M_-, with r, ϕ_3, and δ as free parameters. The method is is therefore directly sensitive to the value of ϕ_3 and it does not require additional assumptions on the values of r and δ. Moreover, the value of r obtained in the fit can be further used in other ϕ_3 measurements.

To fit the $\tilde{D} \rightarrow K_s\pi^+\pi^-$ Dalitz plot distributions corresponding to B^+ and B^- decays, we use an unbinned maximum likelihood technique with the model of neutral D decay determined from a flavor-tagged D sample from continuum $D^{*\pm} \rightarrow D\pi_s^{\pm}$ decay. The drawback of this approach is that only the absolute value of the D^0 decay amplitude f is determined directly, but the complex form of f can be obtained only with certain model assumptions, leading to substantial model uncertainties in the determination of ϕ_3. These uncertainties, however, can be controlled in future using data from $c\tau$-factories. The sample of neutral D mesons in a CP eigenstate, which can be produced in the decay of $\psi(3770)$ resonance, will provide the information about the complex phase of amplitude f which is needed for model-independent measurement of ϕ_3.

2   Event selection

For our measurement we use the 140 fb^{-1} of data collected by the Belle detector.[5] The decays $B^{\pm} \rightarrow DK^{\pm}$ and $B^{\pm} \rightarrow D^*K^{\pm}$, $D^{*0} \rightarrow D^0\pi^0$ are selected for the determination of ϕ_3. We require D^0 to decay to the $K_s\pi^+\pi^-$ final state in all cases. Also, we select decays of $D^{*\pm} \rightarrow D\pi_s^{\pm}$ produced in the continuum for the determination of the $\bar{D}^0 \rightarrow K_s\pi^+\pi^-$ decay amplitude.

To determine the $\bar{D}^0$ decay model we use $D^{*\pm}$s produced via the $e^+e^- \rightarrow c\bar{c}$ continuum process. The flavor of the neutral D meson is tagged by the charge of the slow pion π_s in the decay $D^{*\pm} \rightarrow D\pi_s^{\pm}$. To select neutral D candidates we require the invariant mass of the $K_s\pi^+\pi^-$ system to be within 9 MeV/c^2 of the D^0 mass, M_{D^0}. To select the events originating from the $D^{*\pm}$ decay we make a requirement on the difference ΔM of the invariant masses of the neutral D and $D^{*\pm}$ candidates: 144.6 MeV/$c^2 < \Delta M < 146.4$ MeV/c^2. To suppress the combinatorial background from $B\bar{B}$ events, we require the $D^{*\pm}$ to have momentum in the center-of-mass (CM) frame greater than 2.7 GeV/c. The number of events passing selection criteria is 104204. The fit of the ΔM distribution yields the background fraction of 3.09±0.05%.

Selection of B candidates uses the CM energy difference $\Delta E = \sum E_i - E_{beam}$ and the beam-constrained B mass $M_{bc} = \sqrt{E_{beam}^2 - (\sum p_i)^2}$, where E_{beam} is the CM beam energy, and E_i and p_i are the CM energies and momenta of the B candidate decay products. The requirements for signal candidates are 5.272 GeV/$c^2 < M_{bc} < 5.288$ GeV/c^2 and $|\Delta E| < 0.022$ GeV. In addition, we make a requirement on the invariant mass of the neutral D candidate: $|M_{K_s\pi\pi} - M_{D^0}| < 11$

MeV/c^2. To suppress the continuum background, we require $|\cos\theta_{thr}| < 0.8$, where θ_{thr} is the angle between the thrust axis of the B candidate and the rest of the event. For additional background rejection, we use a Fisher discriminant based on "virtual calorimeter".[6]

The selection efficiency of the $B^\pm \to DK^\pm$ process is determined from a Monte Carlo (MC) simulation of the detector and amounts to 11%. The number of events passing all selection criteria is 146. The background fraction extracted from the fit of ΔE distribution is $25 \pm 4\%$.

For the selection of $B^\pm \to D^*K^\pm$ events in addition to the requirements described we require the mass difference $\Delta M = M_{K_s\pi^+\pi^-\pi^0} - M_{K_s\pi^+\pi^-}$ of neutral D^* and D candidates to satisfy 140 MeV/$c^2 < \Delta M < 145$ MeV/c^2. The selection efficiency is 6.2%, and the number of events satisfying selection criteria is 39. The background fraction is $12 \pm 4\%$.

3 Determination of $\bar{D}^0 \to K_s\pi^+\pi^-$ decay model

The amplitude f of the $\bar{D}^0 \to K_s\pi^+\pi^-$ decay is represented by a coherent sum of two-body decay matrix elements, each having its own amplitude and phase, plus one non-resonant decay amplitude. The total phase and amplitude are arbitrary. To be consistent with the CLEO analysis,[7] we have chosen the $K_s\rho$ mode to have unit amplitude and zero relative phase. The description of the matrix elements follows Ref. [8]

For our D^0 model fit we use a set of 15 two-body amplitudes. These include four Cabibbo-allowed amplitudes: $K^*(892)^+\pi^-$, $K_0^*(1430)^+\pi^-$, $K_2^*(1430)^+\pi^-$ and $K^*(1680)^+\pi^-$, their doubly Cabibbo-suppressed partners, and seven channels with K_s and a $\pi\pi$ resonance: $K_s\rho$, $K_s\omega$, $K_sf_0(980)$, $K_sf_2(1270)$, $K_sf_0(1370)$, $K_s\sigma_1$ and $K_s\sigma_2$. The masses and Breit-Wigner widths of scalars σ_1 and σ_2 are left unconstrained, while the parameters of other resonances are taken to be the same as in the CLEO analysis.[7] The parameters of the σ resonances obtained in the fit are as follows: $M_{\sigma_1} = 539 \pm 9$ MeV/c^2, $\Gamma_{\sigma_1} = 453 \pm 16$ MeV/c^2, $M_{\sigma_2} = 1048$ MeV/c^2, $\Gamma_{\sigma_2} = 109 \pm 11$ MeV/c^2. The resonance σ_2 was introduced to describe a structure in the Dalitz distribution possibly due to the decay $f_0(980) \to \eta\eta$ with the rescattering of $\eta\eta$ to $\pi^+\pi^-$.

We use the unbinned maximum likelihood technique to fit the Dalitz plot distribution. The fit function for the Dalitz plot density is represented by a sum of the squared absolute value of the decay amplitude $|f(m_+^2, m_-^2)|^2$ and the background distribution, convoluted with a momentum resolution function and multiplied by the function describing efficiency. The free parameters of the minimization are the amplitudes and phases of the resonances, and the amplitude and phase of the non-resonant component. The background density for $\bar{D}^0 \to K_s\pi^+\pi^-$ events is obtained from ΔM sidebands. The shape of the efficiency over the Dalitz plot is extracted from a MC simulation. The fit result is presented in Table 1.

4 Dalitz plot analysis of $B^\pm \to D^{(*)}K^\pm$ decay

The Dalitz plots of $\tilde{D}$ decaying to $K_s\pi^+\pi^-$, which contain information about CP violation in B decays, are fitted by minimizing the combined logarithmic likelihood function for B^- and B^+ data sets. The corresponding Dalitz plot densities are based on decay amplitudes $M_\pm$ described by Eq. 1 (B^+ data) and 2 (B^- data). The $\bar{D}^0$ decay model f is fixed, and the free parameters of the fit are the amplitude ratio r and phases ϕ_3 and δ.

Since the background rate is significant, it is essential to include the background density into the fit model. The largest background contribution comes from continuum $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) events. It includes background with purely combinatorial tracks, and continuum D^0 mesons combined with a random kaon. This type of background is analyzed using an event sample in which $\cos\theta_{thr}$ and Fisher discriminant requirements are applied in order to select continuum events. The continuum background fraction is $22.1 \pm 3.9\%$ for $B^\pm \to DK^\pm$ mode and $9.0 \pm 3.6\%$ for $B^\pm \to D^*K^\pm$ mode. The background due to $B\bar{B}$ combinatorics was investigated

Table 1: Fit results for $\bar{D}^0 \to K_s \pi^+ \pi^-$ decay. Errors are statistical only.

Intermediate state	Amplitude	Phase (°)
$K^*(892)^+\pi^-$	1.656 ± 0.012	137.6 ± 0.6
$K^*(892)^-\pi^+$	$(14.9 \pm 0.7) \times 10^{-2}$	325.2 ± 2.2
$K_0^*(1430)^+\pi^-$	1.96 ± 0.04	357.3 ± 1.5
$K_0^*(1430)^-\pi^+$	0.30 ± 0.05	128 ± 8
$K_2^*(1430)^+\pi^-$	1.32 ± 0.03	313.5 ± 1.8
$K_2^*(1430)^-\pi^+$	0.21 ± 0.03	281 ± 9
$K^*(1680)^+\pi^-$	2.56 ± 0.22	70 ± 6
$K^*(1680)^-\pi^+$	1.02 ± 0.2	103 ± 11
$K_s\rho^0$	1.0 (fixed)	0 (fixed)
$K_s\omega$	$(33.0 \pm 1.3) \times 10^{-3}$	114.3 ± 2.3
$K_s f_0(980)$	0.405 ± 0.008	212.9 ± 2.3
$K_s f_0(1370)$	0.82 ± 0.10	308 ± 8
$K_s f_2(1270)$	1.35 ± 0.06	352 ± 3
$K_s\sigma_1$	1.66 ± 0.11	218 ± 4
$K_s\sigma_2$	0.31 ± 0.05	236 ± 11
non-resonant	6.1 ± 0.3	146 ± 3

using the MC simulation. The fraction of $B\bar{B}$ background is $3.6 \pm 0.3\%$ for $B^\pm \to DK^\pm$ mode and $3.1 \pm 0.4\%$ for $B^\pm \to D^*K^\pm$ mode.

To test the consistency of the fit, the same procedure was applied to the $B^\pm \to \tilde{D}^{(*)}\pi^\pm$ and $\bar{B}^0(B^0) \to D^{*\pm}\pi^\mp$ control samples as to the $B^\pm \to \tilde{D}^{(*)}K^\pm$ signal. For decays of flavor eigenstate of D meson, our fit should return r values consistent with zero. In the case of $B^\pm \to \tilde{D}^{(*)}\pi^\pm$ a small amplitude ratio is expected ($r \sim |V_{ub}V_{cd}^*|/|V_{cb}V_{ud}^*| \sim 0.02$). Deviations from these values can appear if the Dalitz plot shape is not well described by the fit model. For the control sample fits, we consider B^+ and B^- data separately, to check for the absence of CP violation. In the fit of $B^\pm \to \tilde{D}\pi^\pm$ data, we obtain $r \sim 0.06$ which is more than two standard deviations apart from zero, however, no CP asymmetry is found. This bias is considered as a systematic effect. Other control samples, $B^\pm \to \tilde{D}^*\pi^\pm$ with D^{*0} decaying to $D^0\pi^0$, and $\bar{B}^0(B^0) \to D^{*\pm}\pi^\mp$ with $D^{*\pm} \to D^0\pi^\pm$, do not show any significant deviation from $r = 0$.

The combined unbinned maximum likelihood fit of B^+ and B^- samples with free parameters r, ϕ_3 and δ yields the following values: $r = 0.31 \pm 0.11$, $\phi_3 = 86° \pm 17°$, $\delta = 168° \pm 17°$ for the $B^\pm \to \tilde{D}K^\pm$ sample and $r = 0.34 \pm 0.14$, $\phi_3 = 51° \pm 25°$, $\delta = 302° \pm 25°$ for the $B^\pm \to \tilde{D}^*K^\pm$ sample. The method has a two-fold ambiguity ($\phi_3 + \pi$, $\delta + \pi$), since this transformation does not change the total phases, which are actually measured. Here we choose the solution with $0 < \phi_3 < \pi$.

The errors presented above are the estimation obtained from the likelihood fit. For a more reliable estimation of the statistical errors we use a Bayesian approach with the probability density function (PDF) of the fitted parameters obtained from a large number of MC pseudo-experiments. The MC procedure consists of a generation of two Dalitz plot samples of D^0-$\bar{D}^0$ mixture (with total opposite flavor phases $\delta - \phi_3$ and $\delta + \phi_3$) with the efficiency, momentum resolution and background taken into account as in the fit of experimental data, with a subsequent fitting of this samples to extract the values of r, ϕ_3 and δ. The number of events in the samples is taken nearly equal to the number of events in the experimental data. This procedure was repeated in several hundred trials for different values of input r parameter. The PDF is then parameterized to obtain the function describing the probability density of the reconstructed parameters for any set of true parameters. After the fitted parameters PDF is obtained, we assume a flat prior PDF and calculate the PDF for the true parameters. This procedure not only allows to obtain more reliable estimation of errors, but also corrects the systematic bias of the value of r introduced by the fit procedure due to its positive definiteness.
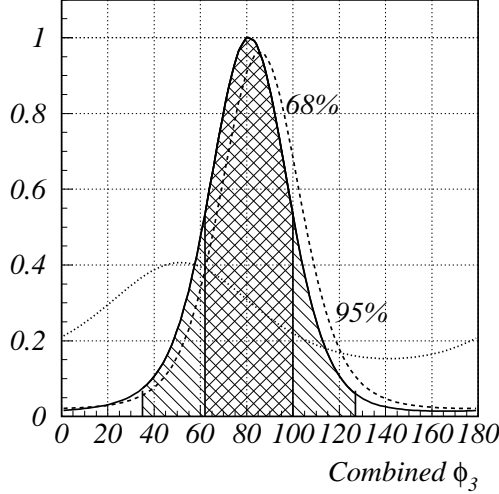
Figure 1: ϕ_3 probability density function for $B^\pm \rightarrow DK^\pm$ (dashed line), $B^\pm \rightarrow D^*K^\pm$ (dotted line) and combined measurement (solid line).

The result of the fit with errors (68% confidence level) obtained from the "toy" MC are as follows: $r = 0.28^{+0.09}_{-0.11}$, $\phi_3 = 86 \pm 20°$, $\delta = 168 \pm 20°$ for $B^\pm \rightarrow DK^\pm$ and $r < 0.25$, $\phi_3 = 51 \pm 47°$, $\delta = 302 \pm 47°$ for $B^\pm \rightarrow D^*K^\pm$. The 95% confidence intervals are $0.07 < r < 0.45$, $37° < \phi_3 < 135°$, $119° < \delta < 217°$ for $B^\pm \rightarrow DK^\pm$ and $r < 0.44$, $-31° < \phi_3 < 133°$, $220° < \delta < 384°$ for $B^\pm \rightarrow D^*K^\pm$. The significance of CP violation is 94% for $B^\pm \rightarrow DK^\pm$ and 38% for $B^\pm \rightarrow D^*K^\pm$. Though the 68% CL error is quite small, the significance is comparatively low due to longer tails of the PDF compared to the gaussian distribution.

We produce the combined measurement of ϕ_3 by multiplying the ϕ_3 PDFs for $B^\pm \rightarrow DK^\pm$ and $B^\pm \rightarrow D^*K^\pm$ modes. The resulting PDF, as well as the PDFs for individual measurements are shown in Fig. 1. The result of the combined measurement is $\phi_3 = 81 \pm 19°$, the 95% confidence interval is $35° < \phi_3 < 127°$.

The model used for the $\bar{D}^0 \rightarrow K_s\pi^+\pi^-$ decay is one of the main sources of systematic errors for our analysis. The model is a result of the experimental Dalitz plot fit, but since the plot density is proportional to the squared absolute value of the decay amplitude, the phase $\phi(m^2_+, m^2_-)$ of the complex amplitude is not directly measured in the experiment. The phase dependence is therefore the result of model assumptions and its uncertainty may affect the $\tilde{D}$ Dalitz plot fit. To estimate the model uncertainties, a MC simulation is performed. Event samples are generated according to the amplitude described by Eq. 1 with the resonance parameters extracted from our fit of continuum D^0 data, but to fit this distribution different models for $f(m_+, m_-)$ are used. We scan the phases ϕ_3 and δ in their physical regions and take the maximum deviation of the fit parameter as a model uncertainty estimation. Since the Breit-Wigner amplitude, on which the $\bar{D}^0$ model is based, can describe well only the narrow resonances, our estimation of the model uncertainty is based on the fit model containing only the narrow resonances, with the wide ones approximated by the constant complex term. The estimated value of the systematic uncertainty on ϕ_3 is 11°.

Other sources of systematic errors include the uncertainties of the knowledge of the detector response, background estimation and possible fit biases. The component related to the background shape parameterization is estimated by extracting the background shape from the M_D sidebands and by using a flat background distribution. To estimate the contributions of efficiency shape evaluation and momentum resolution to the systematic error, we repeat the fit using a flat efficiency and a fit model which does not take the resolution into account, respectively.

The non-zero amplitude ratio observed in the $B^\pm \rightarrow D\pi^\pm$ control sample can be either

due to the statistical fluctuation or may indicate some systematic effect such as background structure or a deficiency of the $\bar{D}^0$ decay model. Since the source of this bias is indeterminate, we conservatively treat it as an additional systematic effect. The corresponding bias of the weak and strong phases is $11°$. This contribution dominates in the systematic error, which equals to $13°$ for $B^\pm \to DK^\pm$ and $11°$ for $B^\pm \to D^*K^\pm$ mode.

5 Conclusion

We have studied a new method to measure the unitarity triangle angle ϕ_3 using Dalitz plot analysis of the three-body D^0 decay in the process $B^\pm \to D^{(*)}K^\pm$. The first measurement of ϕ_3 using this technique was performed based on 140 fb^{-1} statistics collected by the Belle detector. From the combined fit of $B^\pm \to DK^\pm$ and $B^\pm \to D^*K^\pm$ modes, we obtain the value of $\phi_3 = 81° \pm 19° \pm 13° \pm 11°$. The first error is statistical, the second is experimental systematics and the third is model uncertainty. The 95% confidence interval is $35° < \phi_3 < 127°$ The statistical significance of the CP violation is 94% for $B^\pm \to DK^\pm$ mode and 38% for $B^\pm \to D^*K^\pm$ mode.

The method has a number of advantages over the other ways to measure ϕ_3.[2] It is directly sensitive to the value of ϕ_3 and has only the two-fold discrete ambiguity $(\phi_3 + \pi, \delta + \pi)$. It does not involve branching fraction measurements and, therefore, the influence of the detector systematics is lower. Also, the statistical power of this technique is higher in the presence of the background since the interference term is measured.

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